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# **Cryogenic Impinging Jets Subjected to High Frequency Transverse Acoustic Forcing in a High Pressure Environment**

**24-27 July 2016  
Joint Propulsion Conference**



**Mario Roa, Sierra Lobo, Inc.  
Alex Schumaker, AFRL  
Doug Talley, AFRL**



# Objectives



- **Study impinging jets, with N<sub>2</sub> as the working fluid, under sub and supercritical conditions.**
- **Vary jet velocity and chamber pressure to identify conditions where impact waves became prominent, for a single geometry.**
- **Study the flow field with high speed back light imaging. Perform dynamic mode decomposition (DMD) analysis to extract natural frequencies.**
- **Study the response of the flow field when driven by acoustic speakers at low amplitude, high frequency standing wave in pressure anti-node and pressure node configuration.**



# Impinging Jet Injector



## Features

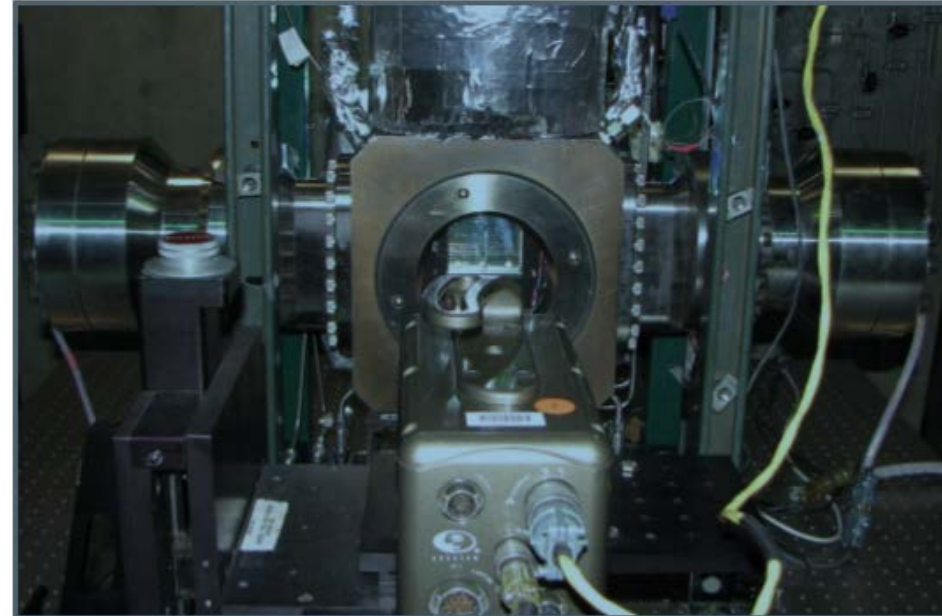
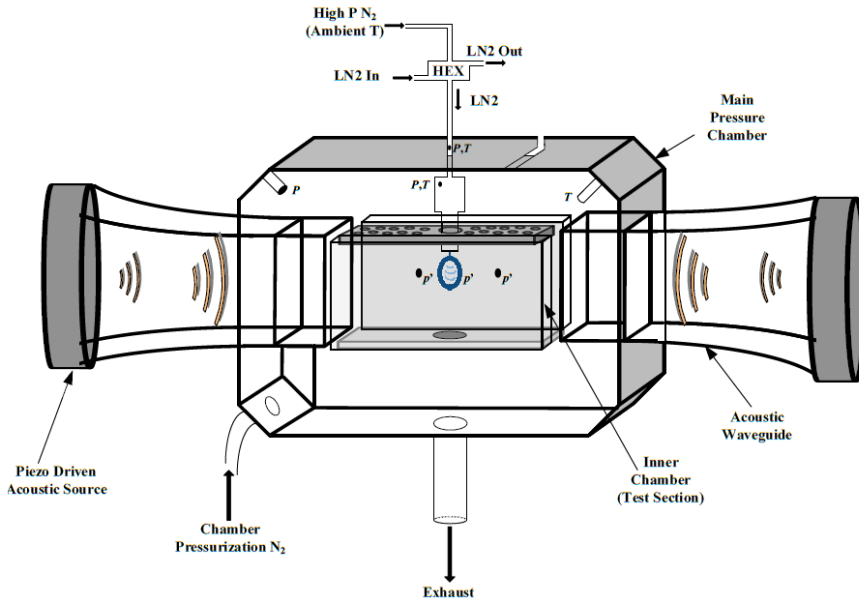
- An injector design where fluid jets strike each other.
- An impingement sheet is formed and impact waves, or surface waves, develop on the surface
- The impinging jet injectors are used to atomize storable liquid rocket engine fuels. They are desirable because of their:
  - Simplicity
  - Low manufacturing cost
  - Good atomization and mixing
- Highly susceptible to instabilities



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# Experimental Facility



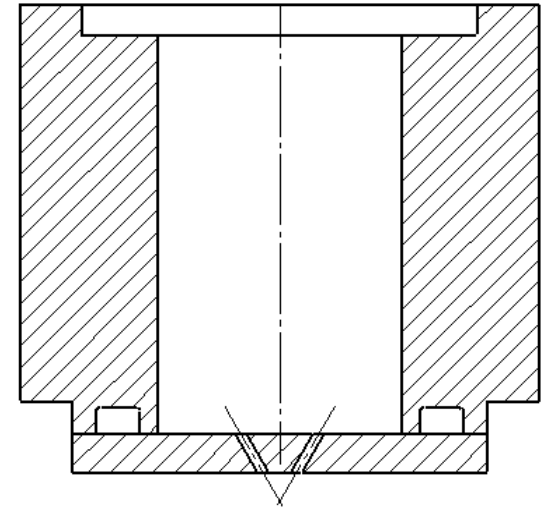
## Features

- Two piezosirens designed for high pressure operation.
- Accurate control of frequency and amplitude of the standing wave. Within  $\pm 0.1$  Hz frequency.
- Multiple high-speed pressure transducers
- A low flow pressurization – accurate control of pressure.
  - Subcritical and supercritical pressures
- Heat changers to create liquid nitrogen – accurate control of temperature to within  $\pm 5$  K.
- On-axis windows for shadowgraph and Schlieren.



# Operating Conditions

- **Vary chamber pressure until impact waves, or surface waves, became prominent on the impingement sheet.**
  - Jet velocities from 0.5 to 15 m/s
  - Chamber pressures of 0 to 4.8 MPa
- **The conditions where impact waves were prominent were for jet velocities of 2 to 5 m/s and chamber pressures of 1 to 1.37 MPa (150 to 200 Psi).**
  - 2 m/s and Chamber pressure of 1.37 MPa was selected for further study ( $Re \# = 7800$  and  $We \# = 270$ ).
- **High speed back-light images were captured at 25kHz.**
- **N<sub>2</sub> jet temperature was kept at a constant 95 K.**
- **Orifice diameter 0.5 mm (0.02in), pre-impingement length 8 I/D and 5 I/D channel length.**
- **Impingement half angle is 30 degrees.**

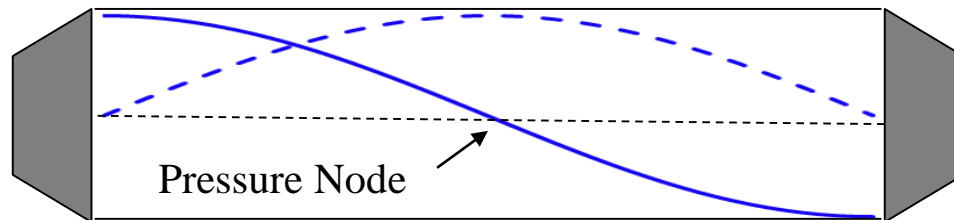




# Forcing Conditions

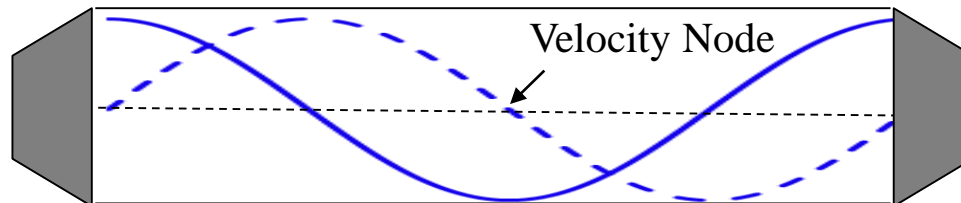
- **Pressure node (PN) and pressure antinode (PAN) at the injector location**

PN



*Imposes transverse velocity oscillation*

PAN



*Imposes unsteady backpressure*

- **Forcing frequency ~ 3000 Hz**
- **Pressure fluctuation amplitudes (peak-to-peak) range up to approximately 9 psi (2% of Chamber Pressure)**



# Parametric Sweep Sub-Critical Results



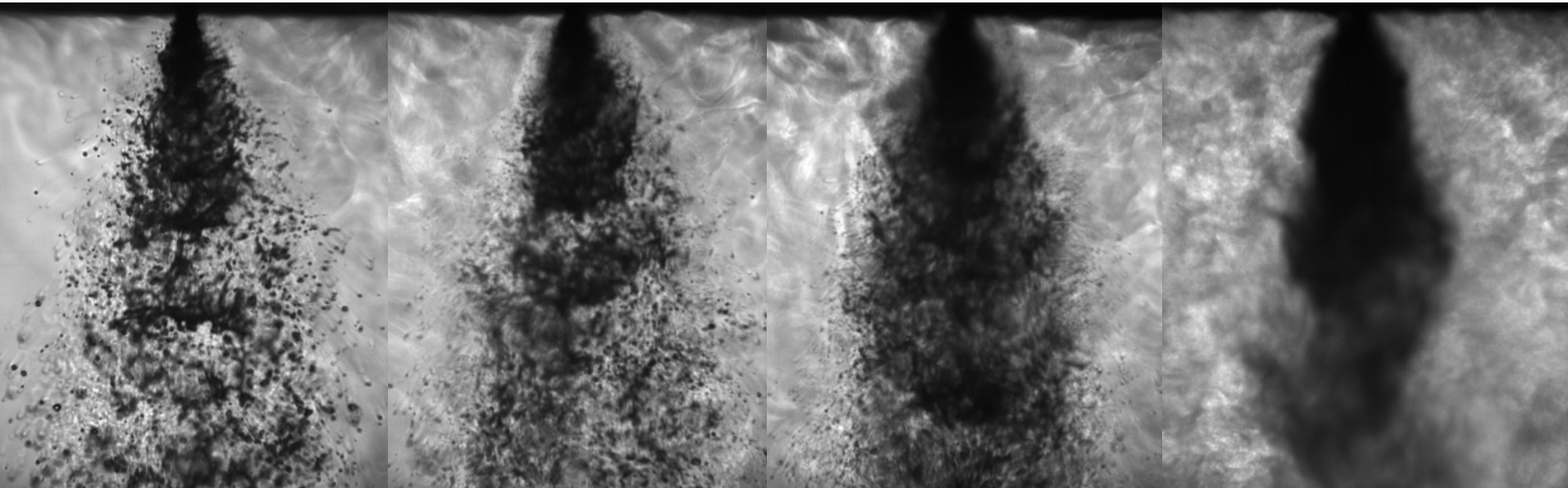
1.72 MPa (250 Psi)

5 m/s

7 m/s

10 m/s

20 m/s



- A droplet size decreases as jet velocity increases
- There are no noticeable structures on the impingement sheet.



# Parametric Sweep Sub-Critical Results



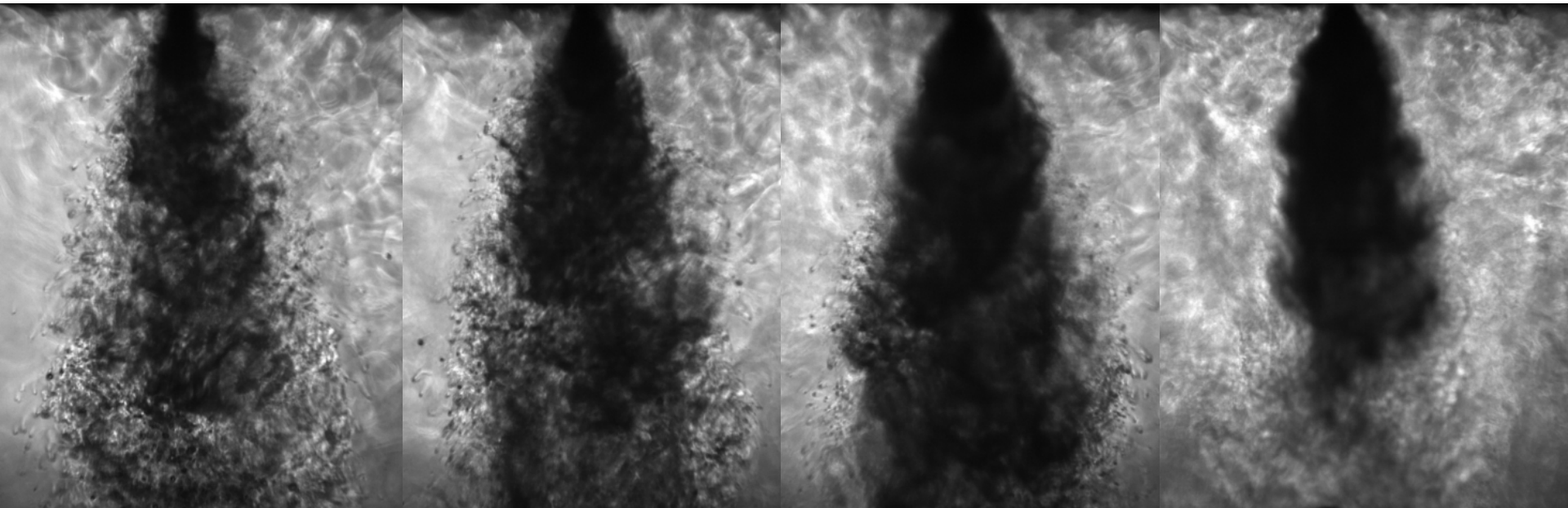
2.58 MPa (375 Psi)

5 m/s

7 m/s

10 m/s

20 m/s



- Transition to a fine mist occurs at lower velocities at high pressures.

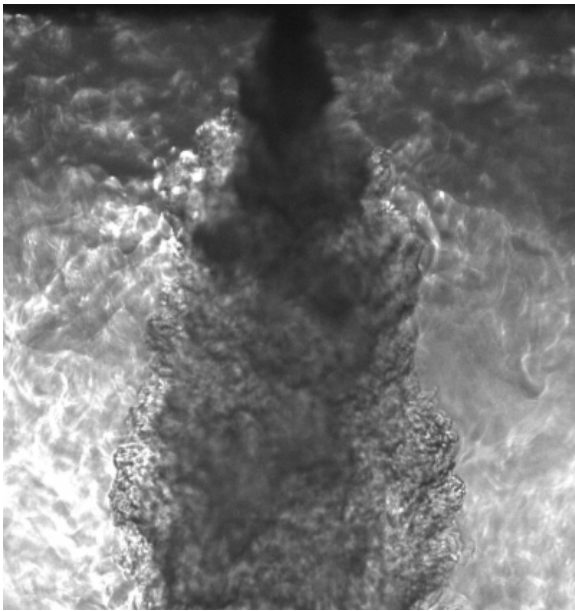


# Parametric Sweep Super-Critical Results

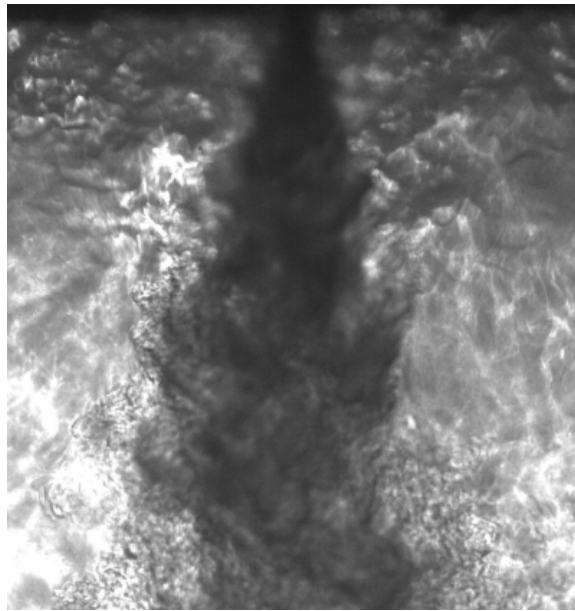


4.82 MPa (700 Psi)

5 m/s



7 m/s



10 m/s

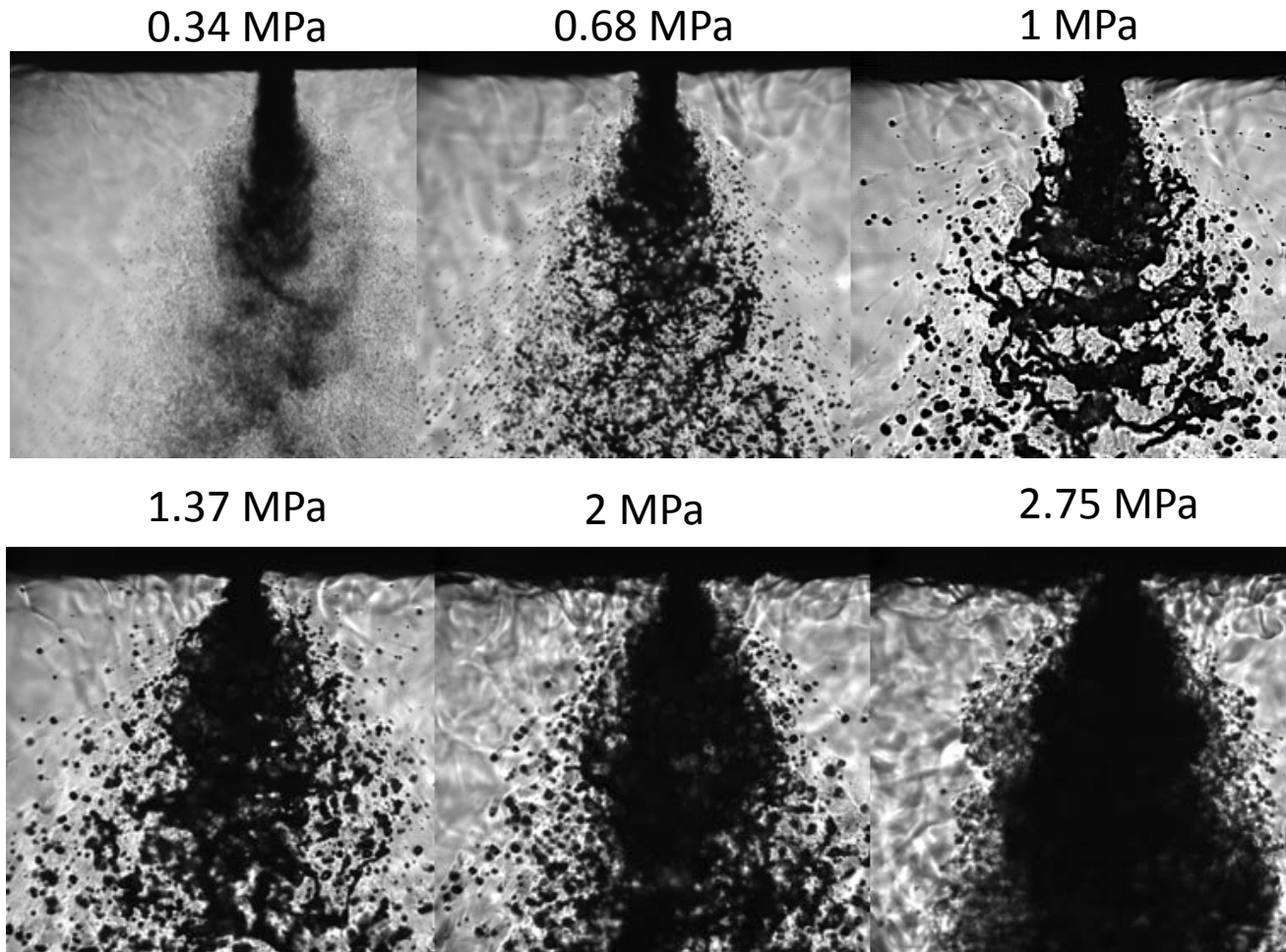


## Differences between subcritical:

- The interface between the surrounding the impingement sheet seem blurred.
- No structure were noticed on the impingement sheet.



# Parametric Sweep 2 m/s Results



- The jet velocity was kept at a constant 2 m/s
- The chamber pressure was increased close to supercritical pressure.
- Impact waves appeared for a narrow range of operating conditions.



# Dynamic Mode Decomposition

Extract spectrally-pure temporal modes with detailed spatial mode shapes

- Schmid (2010) and Rowley et al. (2009)
- Employ time-averaged amplitude measurement described by Alenius (2014)
- 1500 samples used

$$I(x, y, t) = \text{Re} \left( \sum_{i=1}^n \tilde{A}_i \exp(\tilde{\lambda}_i t) \tilde{D}_i(x, y) \right)$$

Amplitude of mode at  $t = 0$

Time average image subtracted from data

Accounts for growth of mode in time as well as temporal frequency

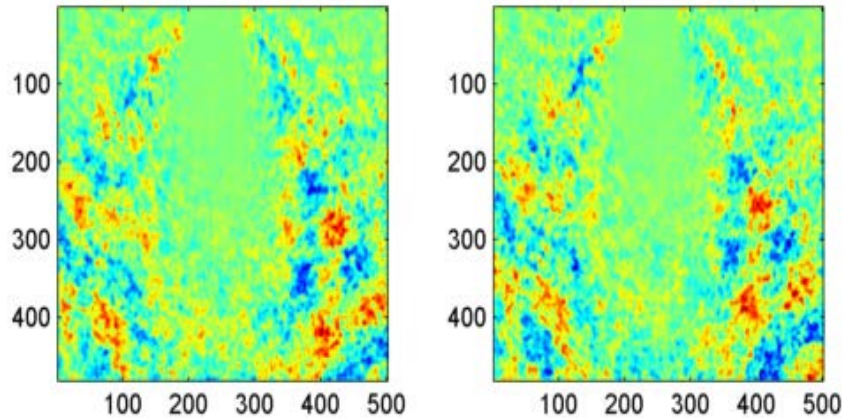
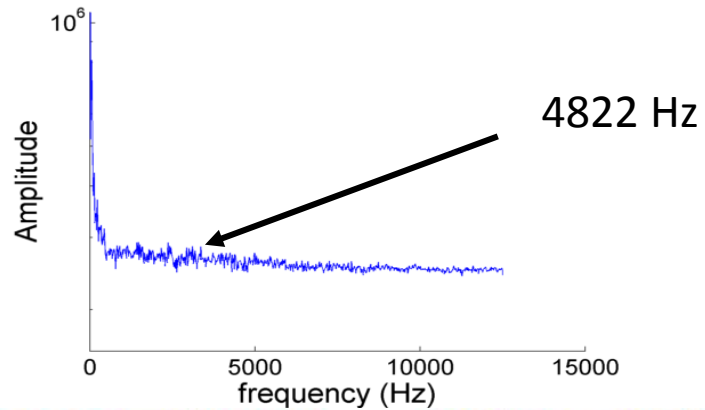
Complex spatial mode shape

## Properties of DMD

- Isolates response of flow at forcing frequency and harmonics
- Single modes can reconstruct convective processes (POD requires two modes)
- Less efficient at reconstructing signal energy compared to POD



# DMD Result, Unforced



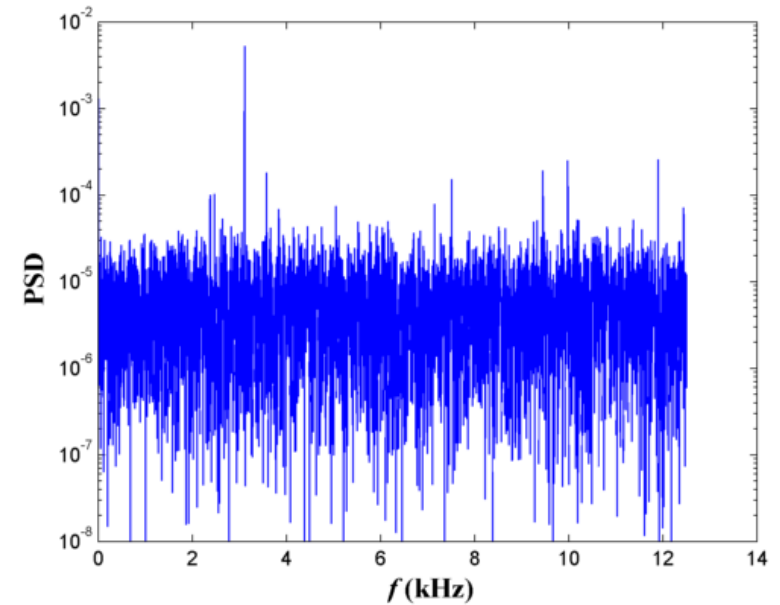
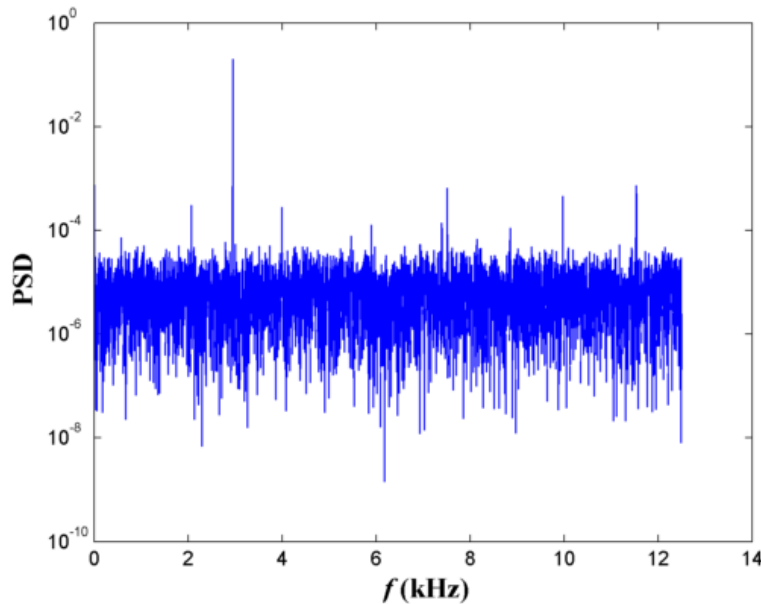
- The jet was kept at a constant 2 m/s at chamber pressure of 1.37 MPa.
- DMD was applied only on the impingement sheet.
- Impact waves were not a dominant feature of the flow field based on the DMD analysis.
- There is a large amount of variability as to when the impact wave detaches and convective velocity.



# PAN Acoustic Forcing

Pressure antinode (PAN)  
forcing @ 2950 Hz

Pressure node (PN)  
forcing @ 3110 Hz



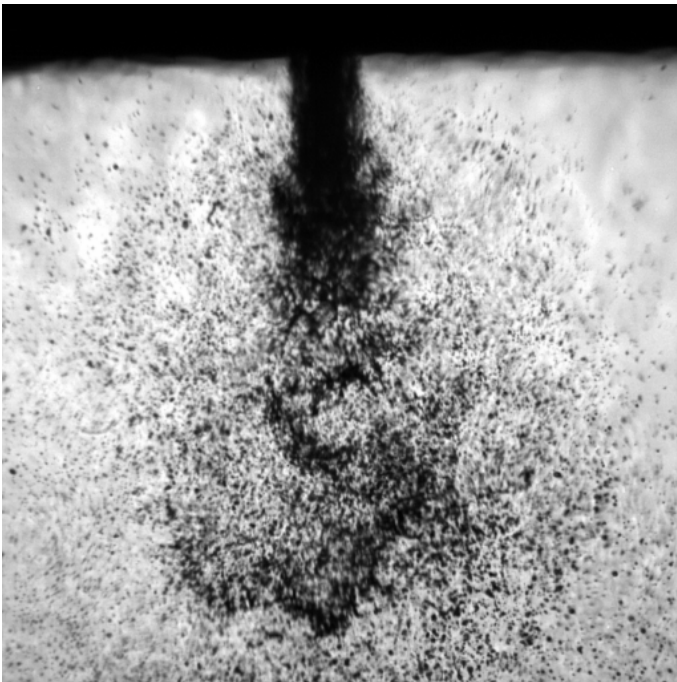


# Acoustic Forcing: Max



PAN Forcing

$$\frac{P'}{\frac{1}{2}\rho u^2} = 58.1$$



PN Forcing

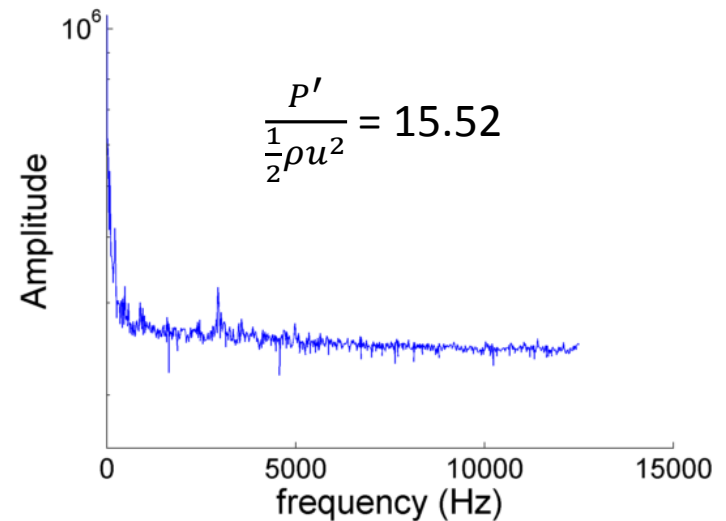
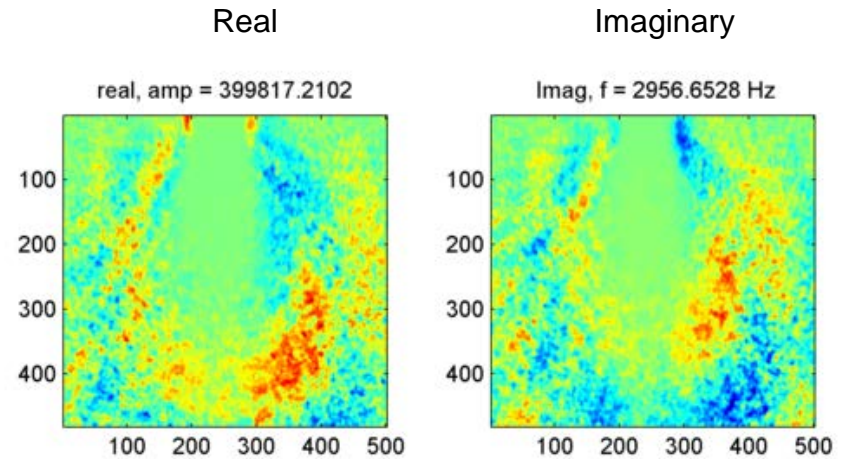
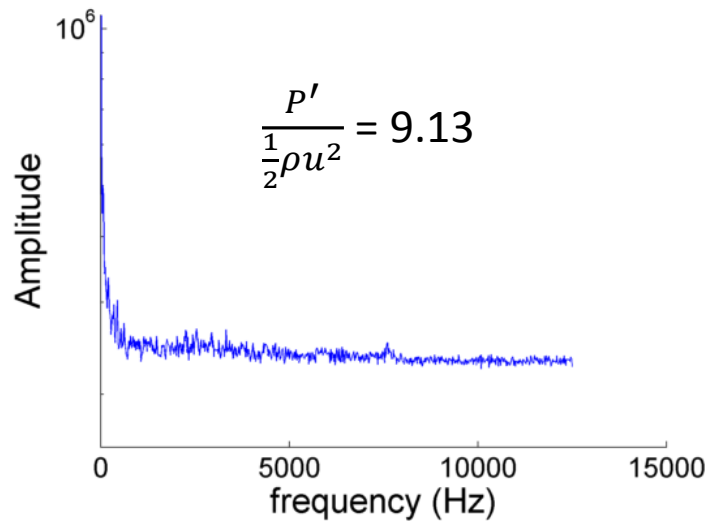
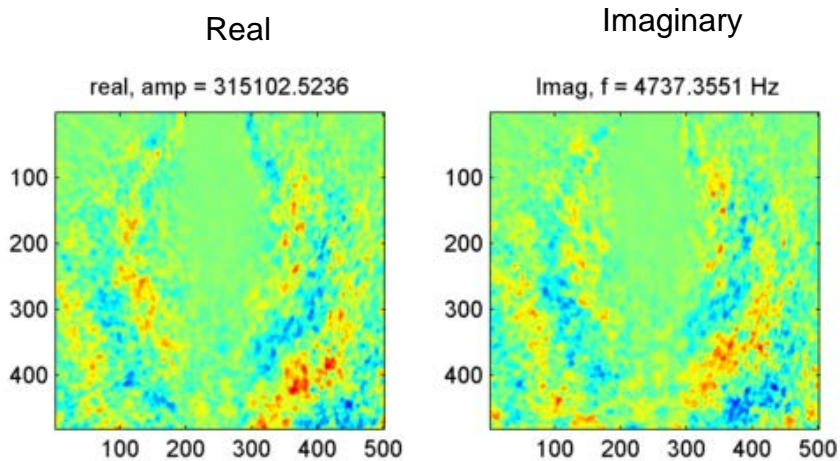
$$\frac{P'}{\frac{1}{2}\rho u^2} = 40$$



- Impact waves appear to vanish at a critical pressure forcing amplitude. The forcing amplitude is different for PAN and PN forcing.



# Forcing PAN: Results



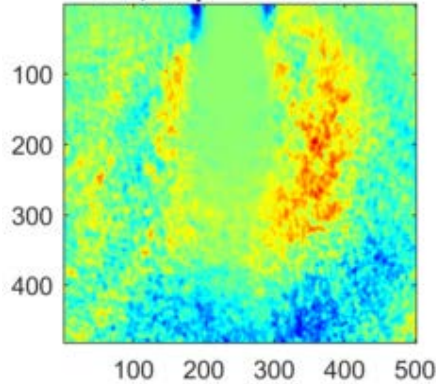
- Impact waves are still present at low level PAN forcing.



# Forcing PAN: Results

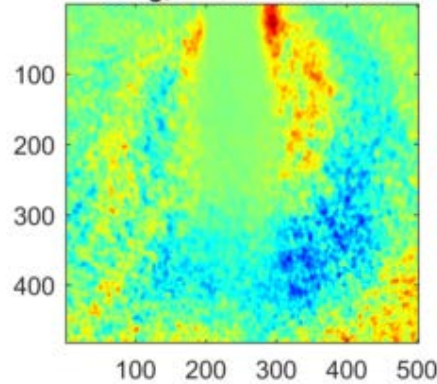
Real

real, amp = 468910.808



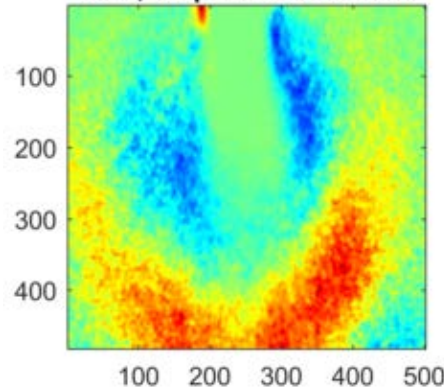
Imaginary

Imag, f = 2921.9125 Hz



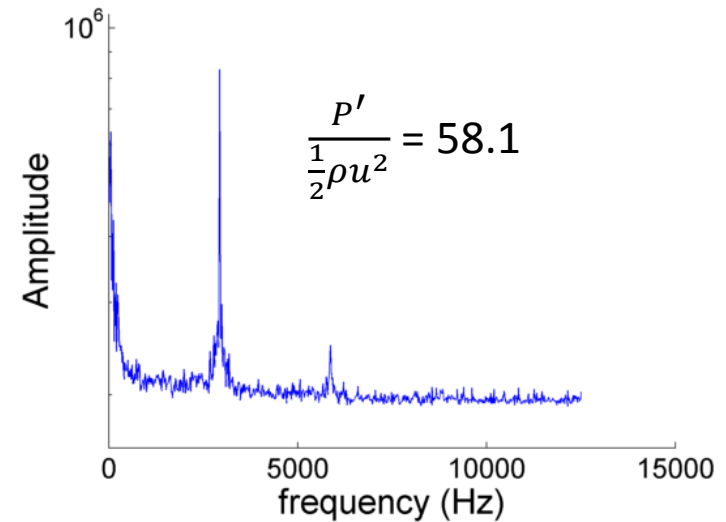
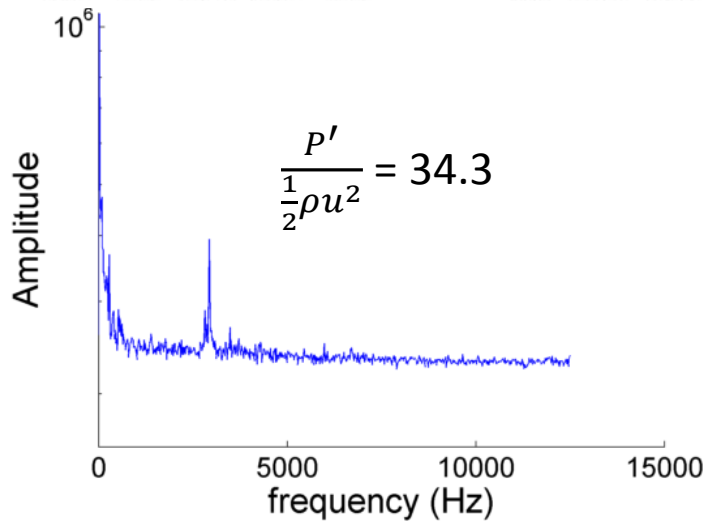
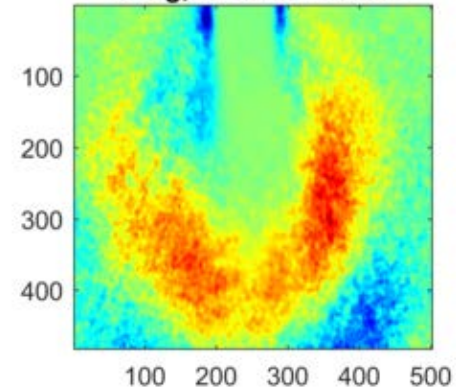
Real

real, amp = 872857.1234



Imaginary

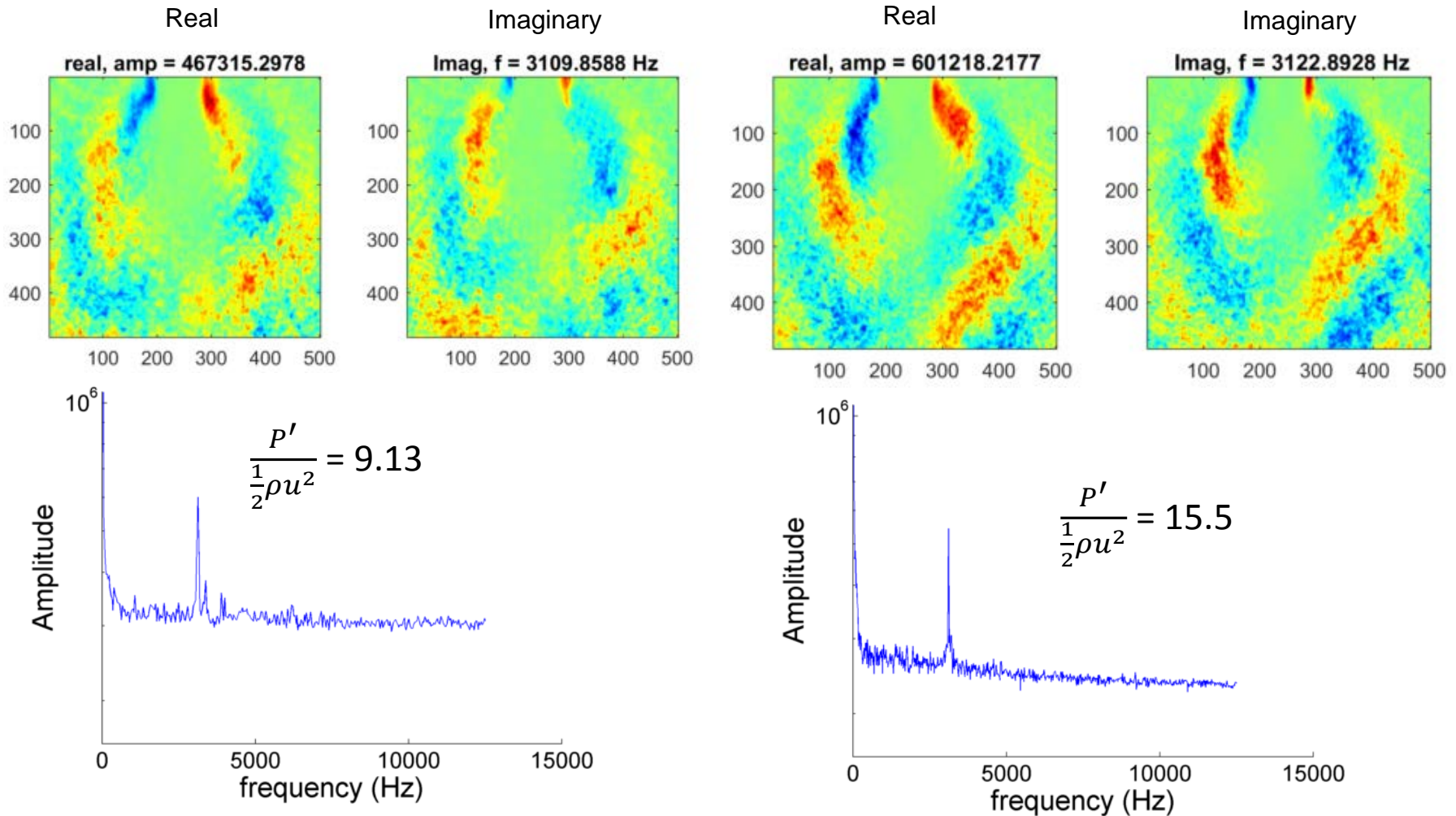
Imag, f = 2925.495 Hz



- Impact waves structures have vanished from the impingement sheet.
- Cyclical mass flow variations dominant the flow field.



# Forcing PN: Results



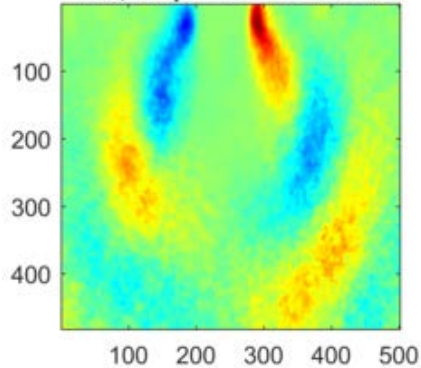
- The impingement sheet responses at lower pressure amplitudes when subjected to PN forcing.



# Forcing PAN: Results

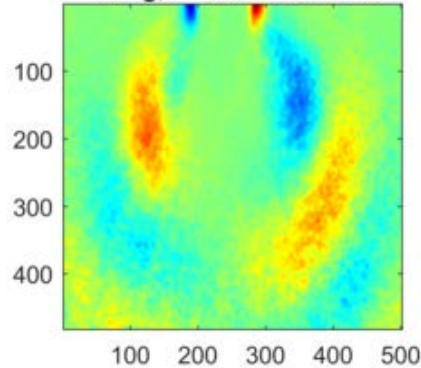
Real

real, amp = 1208360.1212



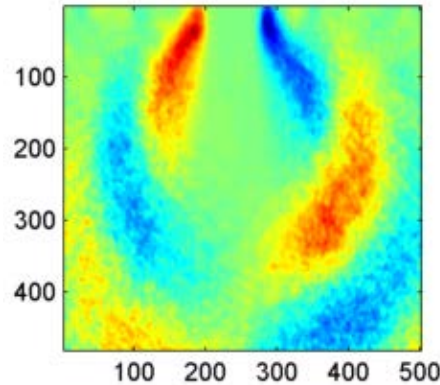
Imaginary

Imag, f = 3115.4498 Hz



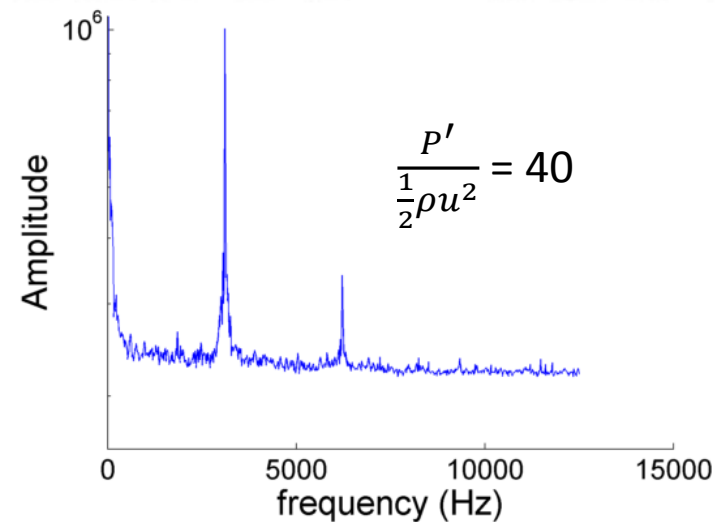
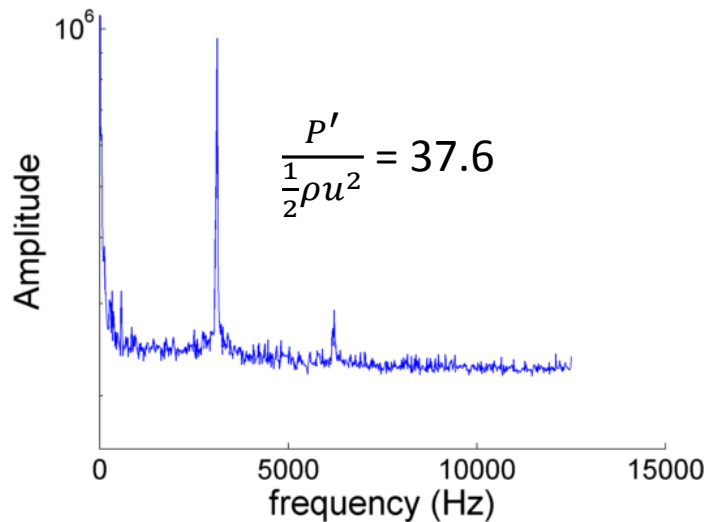
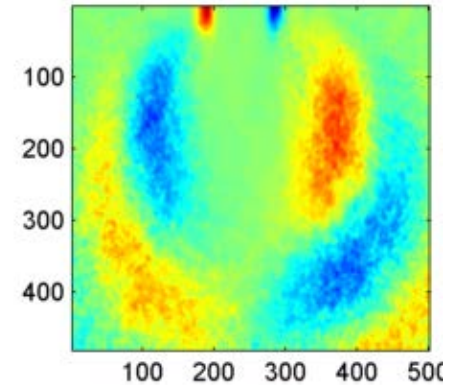
Real

real, amp = 1193184.3813



Imaginary

Imag, f = 3103.1679 Hz



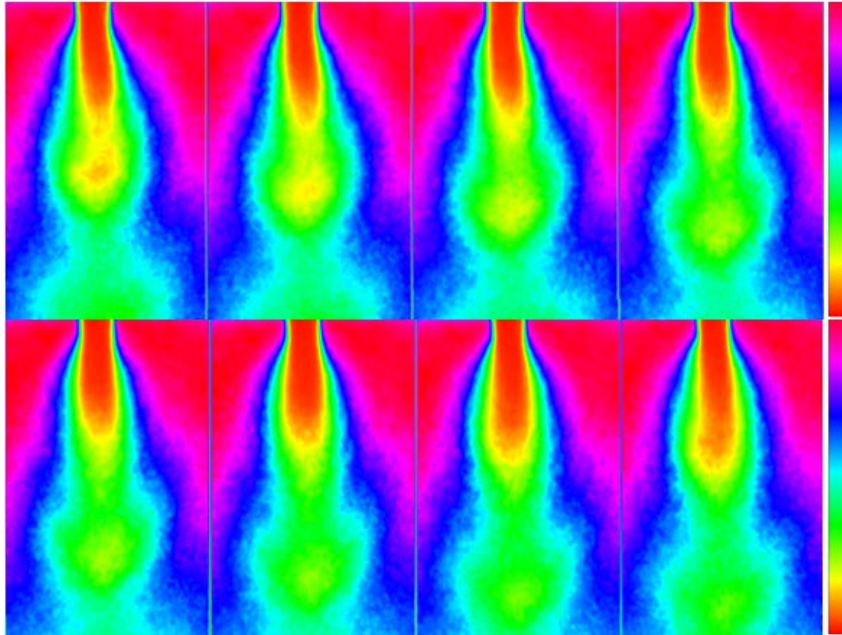
- A swig-swig pattern dominates the impingement sheet. The impingement point moves due to the jets being displaced.
- Impact waves also vanished at a critical pressure amplitude and ligaments are shed due to acoustic forcing.



# Phased Average: Max Forcing

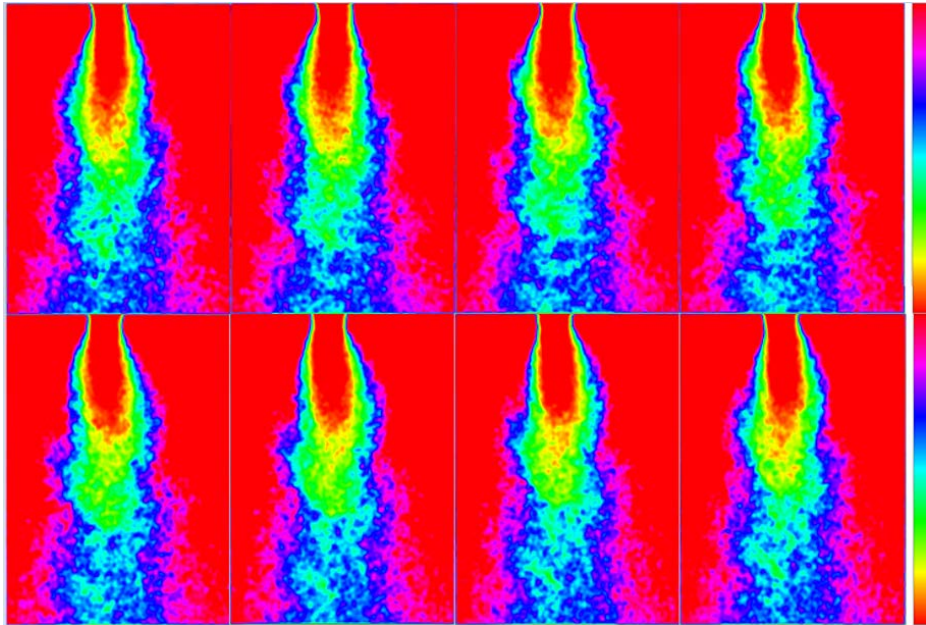
PAN Forcing

$$\frac{P'}{\frac{1}{2}\rho u^2} = 58.1$$



PN Forcing

$$\frac{P'}{\frac{1}{2}\rho u^2} = 40$$



- For the PAN forcing, a large group of droplets are shed at the acoustic forcing frequency due to mass flow variations.
- A swig-swig pattern is present when the impingement sheet is subjected to PN forcing.



# Conclusions, unforced

- **Impact waves, or surface waves, appeared in a narrow range of operating conditions for the given injector.**
- **Dynamic mode decomposition was unable to detect a strong natural frequency associated with impact waves.**
- **For supercritical conditions the injection process and the emerging fluid has to be modelled differently compared to sub-critical conditions**
- **There is large amount of variability from the flow field (convective velocity or ligament separation) to detect a single, strong natural frequency associated with impact wave conditions**



# Conclusions, forced



- **The impingement sheet couples with the acoustics at a certain level of acoustic amplitude**
  - The critical pressure amplitude is different for PAN and PN forcing.
- **Dynamic mode decomposition detected the onset of the coupling and higher harmonics when the forcing was greater than the critical pressure amplitude**
- **PAN forcing:**
  - Mass flow variations
  - Due to the klystron effect results in a “Christmas tree” look.
- **PN Forcing**
  - Results in a swig-swig pattern on the impingement sheet
  - Probably due to a impingement point physically moving



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